14.4 m LARGE APERTURE ANALYSIS MAGNET WITH ALUMINUM COILS

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Abstract - A 14.4 m horizontal field particle analysis magnet, with an aperture 930 mm horizontal x 1200 mm vertical has been designed at Fermilab and is presently under construction. The flux return yoke (1200 t) is fabricated from the yoke of the Nevis cyclotron. The window frame coils provide 813 kA-turns at 4.15 kA. Aluminum conductor, 61.5 mm square, was extruded in 11 m lengths, bent and welded to form turns and layers. The turns were insulated with B-staged epoxy glass tapes cured under pressure.

INTRODUCTION

The conventional dipole magnet described in this paper is presently being fabricated and assembled at the Fermi National Accelerator Laboratory. The large aperture and 30 T-m field integral of the magnet form the basis of a focusing spectrometer which will be used to conduct incisive observations of fundamental interactions. Although the experimental criteria fix the basic parameters of the magnet, a prime consideration at each step in the design has been to minimize the cost. The remainder of this paper describes the resulting design of the aluminum coils and the steel return yoke.

RETURN YOKE DESIGN AND FABRICATION

Yoke Requirements

Physics requirements necessitated a horizontal field and an aperture 930 mm horizontal x 1200 mm vertical x 14.4 m long into which tapered poles, a beam dump and absorbers may be inserted. The steel from the cyclotron at the Nevis Laboratory of Columbia University was to be used for the return yoke.

Yoke Design

The yoke was designed to minimize cutting and machining of the Nevis steel. The weight of the yoke is ∿ 1200 t, of which 98% came from the cyclotron. The yoke is shown in Fig. 1. Stainless steel shelves will bridge the aperture, fitting into horizontal, longitudinal milled cuts in the yoke. These shelves support the upper coils and the aperture inserts.

Yoke Fabrication

The 1800 t Nevis magnet yoke, built in 1947-1950, was composed of 38 machined steel forgings, the heaviest of which weighed 54 t. This steel is used for the yoke of the new magnet. The top, and bottom, of the Nevis yoke was assembled from 10 pieces of steel each measuring 432 mm x 1600 mm x 10 m. These pieces, with the 10 m length cut in half, are utilized to form the upright portions of the new return yoke. Each side of the Nevis yoke contained five pieces of steel, each 864 mm x 1600 mm x 3200 mm. The 3200 mm length was cut to give two pieces 997 mm long, which are used for the bottom and top center of the dipole yoke.

The yoke pieces were cut at Nevis using a commercial flame cutting machine. Oxygen for cutting was supplied either from a liquid dewar or a high pressure tube trailer. The cutting began by preheating the leading edge of the steel for ∿ 10 min. The cutting machine was then turned on and set to travel at a speed of 0.85 mm/s. The speed was reduced for the last 100 mm of the cut.

The steel was shipped by truck from New York to a Chicago fabricator where it was machined. The cut pieces had a residual radioactivity level of < 3 mrad on contact, which required only that Fermilab have a radiation safety technician check at intervals during fabrication and that the machining chips be collected.

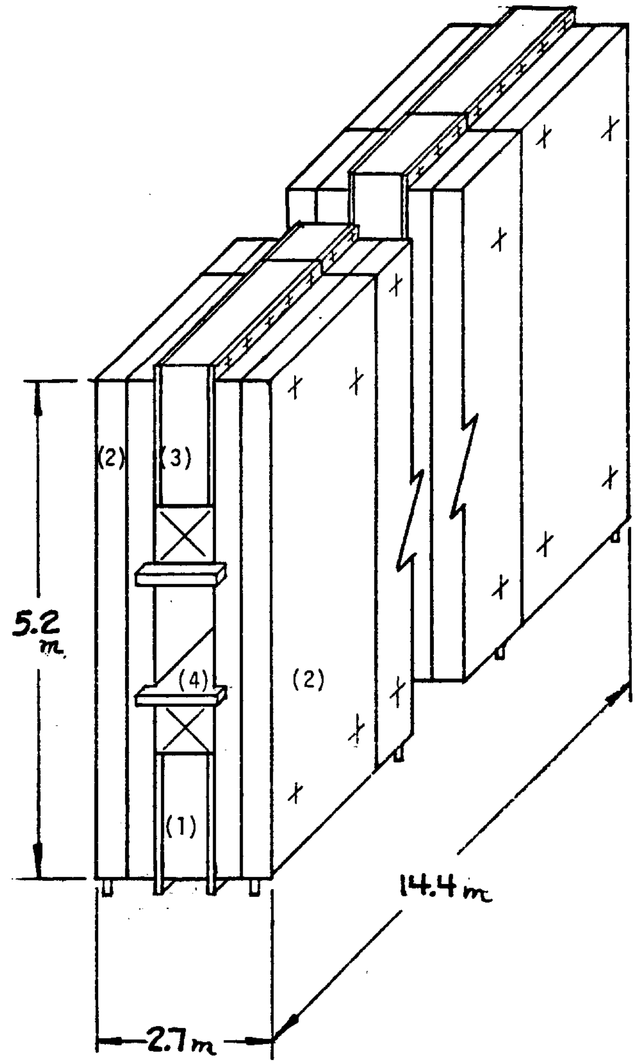

Fig. 1. Steel return yoke. (1) are lower center yoke blocks, (2) are uprights, (3) are upper center yoke blocks, (4) is aperture shelf.

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COIL DESIGN

Coil Requirements

The design goal was for a water-cooled coil of at least 800 kA-turns within a 5000A, 300V power supply limitation. The iron design resulted in a total coil window 930 mm square, shown in Fig. 2. In order to reduce the amount of the coil which extends past the iron, 45° horizontal bends were chosen. Due to the long length of the magnet it was considered impractical to wind the coils in the conventional manner. It was decided to use a bend and weld technique where short lengths of conductor are first bent and then sequentially butt welded to form turns and layers. Since it will be very expensive to repair the coils after installation, long term reliability is also a requirement. The lifetime of the magnet is estimated to be in excess of 10 years.

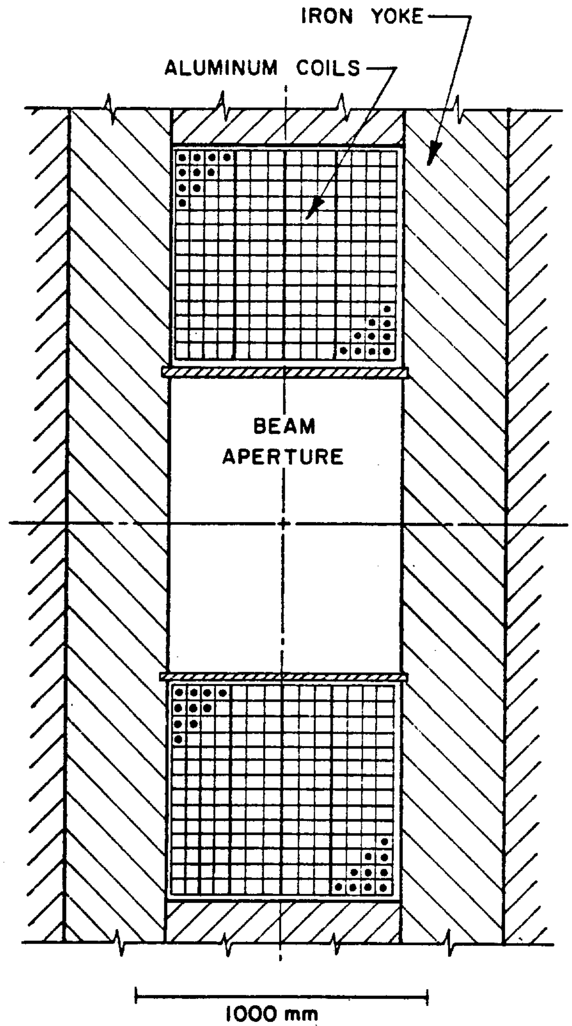

Fig. 2. Coil cross section

Coil Parameters

The choice between copper and aluminum as the conductor material was made on the basis of total cost, i.e., conductor cost plus fabrication cost. The conductor cost may be analayzed with a figure of merit (FOM) = $(NI)^2$/(conductor cost x magnet power). In this case the FOM = $[(\text{density})(\text{cost/weight})(\text{resistivity})]^{-1}$ and is obviously larger for aluminum. It was determined on the basis of experience at SLAC with aluminum and at Fermilab with copper that the fabrication costs are approximately equal. Aluminum was therefore chosen as the conductor material for this magnet. The conductor is shown in Fig. 3, and the coil design parameters are shown in Table I.

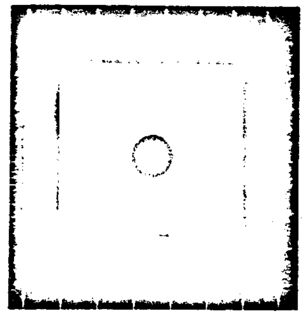

Fig. 3. Aluminum conductor

Table I. Coil Design Parameters

Conductor:	aluminum, 61.5 mm sq x 14 mm ϕ
Conductor required:	69.1 t, 7.85 km
Turns per layer:	14
Total turns:	196
Power supply voltage:	300 circuit is voltage limited
Max. expected I and J:	4150A and 1.15 A/mm^2
Max. expected excitation:	813 kA-turns
Total power:	1200 kW
Inlet water temp & ΔT:	38C and 17C
Water flow:	1000 liters/min

Thermal and Magnetic Stress Analysis

The conductors in the 14.4 m straight section of the coil are subjected to both thermal and magnetic stresses. At design current adjacent conductors are magnetically clamped to each other with a force which varies from 75.7 kN (7.7 t) for the inner conductors to 546.4 kN (55.8 t) for the conductors next to the iron. These forces prevent relative motion between conductors or between conductors and iron as turn-to-turn temperature differences are established. The maximum compressive thermal stress in an elastic conductor is 27.6 MPa, if the coil is permitted to reach the inlet water temperature (38C) before the magnet is energized.

In order to preclude long term damage to the conductor through multiple yielding, the conductor material and welding procedure are such that the magnetically clamped bars remain elastic. The bus conductor alloy 6101-T63 [1] was chosen since it has an elastic limit greater than 70 MPa. The electrical conductivity of this alloy is greater than 57% IACS [2] ($\sim 3 \times 10^{-8}$ Ω-m). Since the turns all have butt welds in the straight sections, a weld procedure has been chosen to insure that the weld heat affected zone behaves elastically to at least 35 MPa. To reduce the thermal stresses by a factor of two, the magnet operating procedure includes that the magnet be momentarily de-energized at intervals during the warm-up time.

Insulation

The insulation in this coil is quite thick to provide mechanical protection against fabrication errors. Inter-turn metal chips and undetected burrs on the conductor are unlikely to cause electrical shorts. Each conductor bar first is wrapped with a half-lapped layer of 0.18 mm polyester-glass tape impregnated with B-staged epoxy resin. The bar is then butt wrapped with 0.75 mm 3M Scotchply, a non-woven fiberglass-reinforced B-staged epoxy resin composite. The coil, or ground wrap is the same as the conductor wrap but with the polyester-glass tape on the outside. Upon curing, the resin flows into crevices and forms a monolithic structure. The total insulation between adjacent conductors or between conductor and iron is 2.24 mm.

Since the magnet has a beam dump in the aperture, the question of radiation damage to the coil, especially to the insulation, is relevant. The coil is approximately 600 mm from the dump. Calculations [3] give a worst-case energy deposition of 2.1 x 10^8 rads per 10^{18} 400 GeV protons absorbed by the dump. Shielding the coils with 25 mm of lead reduces this by a factor of ten. The worst-case dose rate expected is 10^8 rads/year and 10^9 rads over the life of the magnet. Radiation induced degradation of mechanical and electrical properties of fiberglass reinforced epoxy used for coil insulation is not significant below $\sim 10^{11}$ rads [4].

Corrosion [5]

Aluminum is anodic to copper, and therefore aluminum coils are susceptible to galvanic corrosion when cooled with water systems which are also used for copper coils. De-ionizing the low conductivity water system to 0.5 x 10^{-4} mho/mm prevents corrosion. In order to guard against dissimilar metal corrosion, all water fittings and pipes inside the coil are made from the same alloy as the conductor. The aluminum water pipes terminate in accessible stainless steel fittings for connection through rubber hoses to the water system. Impingement and cavitation corrosion rates are insignificant for systems with low flow velocity and de-ionized water.

Water and Electrical Connections

In order to reduce the likelihood of long term water induced coil damage caused by leaking fittings or burst hoses, all water connections are located near the floor. As a safety measure, the electrical connections are made at the top of the coil, approximately 4 m from the floor.

COIL FABRICATION

Basic Technique

The construction of the coils proceeds serially as follows:

1) Extrude and deliver conductor in 11 m lengths.
2) Bend and weld to form layer (14 turns, 112 bends, 56 welds) at outside vendor, deliver to Fermilab.
3) Apply conductor insulation.
4) Weld joints between layers to form 3 or 4 layer coils.
5) Apply ground insulation, clamp and cure.
6) Deliver two 3-layer and two 4-layer coils to the Meson Area for installation.

Aluminum Conductor

The aluminum conductor is specified for alloy and heat treatment and for mechanical and electrical properties. Standard tolerances [3] are specified on the over-all size, hole diameter and placement, flatness, twist, etc. The 789 pieces of conductor are ordered in four discrete lengths. The conductor is extruded from billets 305 mm ϕ x 660 mm on a 2700 t press, stretched, cut to length and heat treated. The solution heat treatment consists of a water quench immediately following extrusion. The precipitation heat treatment to obtain the -T63 condition is 9 h at 210C. The measured yield strength of the finished conductor is 163-220 MPa. The electrical conductivity is 57-61% IACS. The dimensions are all better than specified.

Fabrication of Single Layer

It is recognized that two critical factors in coil fabrication are that the coils must fit into the iron window and that the layers must nest. The conductor packing density in the coil ends is reduced to permit the fabrication tolerances to be relaxed. For example, adjacent turns in the straight section are 2.3 to 3.6 mm apart while in the end section the separation is 6.4-12.7 mm. The 45° bends are dekeystoned to meet the straight section separation. The four welds in each turn are located in the straight and end sections, making it easier to meet the tolerances. The tolerance on the long straight dimensions is ± 6.35 mm. The most critical dimension in a layer is the inside transverse distance, which is held to ± 1.6 mm in order to fit into the magnet. A typical layer is shown in Fig. 4. The individual layers are dimensioned to provide space between layers on the ends so the 90° bends are not dekeystoned. The spaces on end end were larger to accommodate the water pipes which reach inside the coil. All the water piping is located on the downstream end.

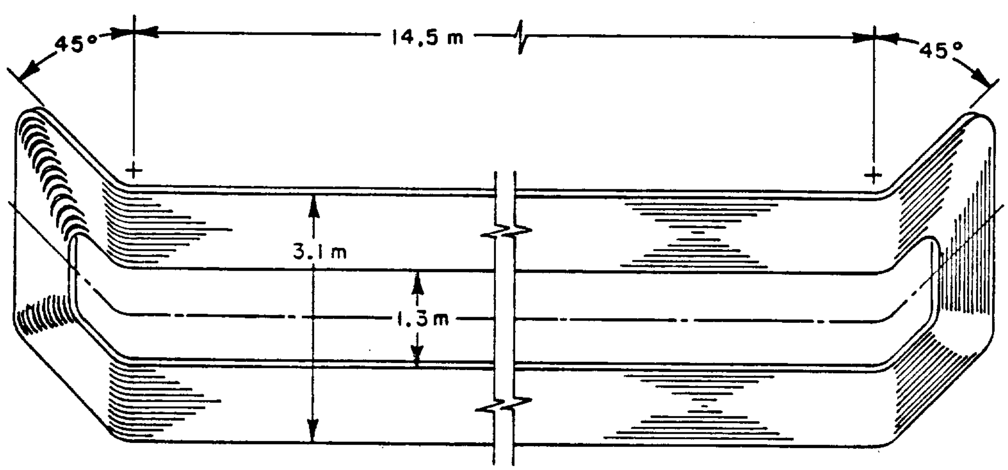

Fig. 4. Single Layer

A 6101-T63 weld sleeve is used to eliminate weld penetration into the cooling water hole, to assist with alignment and to provide a continuous water path of conductor material. The 780 butt welds made by the vendor undergo a four part inspection: (1) An 11 mm ball is blown through the conductor to check for obstructions in the water flow path. (2) The weld is leak tested to the provisions of the ASME Boiler Code [6]. (3) The weld is hydrostatically tested to a pressure of 4 MPa in accordance with the Code [7]. (4) The weld is radiographed in accordance with the Code [8].

Assembly of Layers into 3 and 4 Layer Coils

The layers are assembled into coils at Fermilab. An 18 m assembly and curing fixture is used to maintain dimensions. The first layer is placed ∿ 1 m above the fixture with the ends directed upward. Starting on the inside the turns will be spiraled downward, wrapped with insulation and lowered to the fixture. The water pipes (26.7 mm OD x 18.8 m ID) are welded in place, inspected [6][7] and insulated. Subsequent layers are assembled on top of each other. The coils are ground wrapped with insulation. Steel curing plates 12 mm thick are installed on all four sides of the straight and the end sections and preloaded to provide a curing pressure.

The coil will be heated to the curing temperature by passing a DC current through the conductor. This technique for curing coil insulation has not been used at Fermilab for coils of this size. Consequently, the heating, steady-state curing and cooling phases were analyzed. Based on calculations, the coil to be cured (including the steel clamping plates) is wrapped in a 100 mm fiberglass wool insulating blanket and heated with a 400 kW power supply. Approximately 3500 MJ of heat are added to raise the temperature of a four layer package from 20C to the curing temperature of 150C. Most of this thermal energy (72%) is in the aluminum; the remainder is in the steel clamping plates (17%), in the insulation (6%) and in the fiberglass blanket (5%). The thermal inertia of the metal prevents large or sudden temperature changes. With this power supply, it takes approximately 3 h to heat a four layer package to the curing temperature. The power supplied is not constant, and the resistance of a coil changes by 40% as the temperature rises. Once 150C is reached, heat loss through the blanket is ∿ 8 kilowatts and 560A is adequate to maintain the temperature. At 150C a 1A change in the current causes a temperature change of ∿ 0.6C. It is necessary to keep the insulation at as nearly a uniform temperature as possible during the various phases of the process (heating, curing, cooling). In each phase the maximum temperature difference occurs across the ground wrap. While heating, the maximum temperature difference is less than 5.5C. During the three hour curing phase, this maximum is ∿ 0.5C. The blanket is removed during the cooling phase so that the coil and steel clamping plates can cool more quickly. During this phase, the maximum temperature difference is less than 8.5C. With natural convection and radiation heat transfer, it takes about 4 hours to decrease the temperature to 100C, and 36 hours to reach 26C. Forced convection is provided after ∿ 8 h to shorten the cooling time. Following the curing process, the layer-to-layer spaces in the coil end sections are filled with a loaded epoxy and cured at room temperature. Each completed 3-layer coil weighs ∿ 18 t and each 4-layer coil ∿ 23 t.

YOKE AND COIL INSTALLATION

The assembly of the magnet in the Meson Detector Building began in March 1981 in a pit ∿ 1 m below floor level. The pit floor, 1 m thick reinforced concrete, provides longitudinal stiffness for the magnet and distributes the weight. Steel base plates, leveled and grouted, provide a common plane for all magnet components. Assembly begins with the installation of nine lower center yoke blocks, Fig. 1. They are aligned and welded to each other as well as to the base plates. A double wall of 18 uprights are erected on the east side of the center blocks. They are bolted and welded to each other and to the center blocks to provide stability. The stainless steel aperture shelves are installed and supported by temporary brackets.

Each completed coil is moved out of the assembly building, and a handling and installation fixture attached. The fixture, made of 5083 aluminum alloy [1] weighs 4 t. The coil and fixture are loaded on a 18 m trailer with a straddle lift and moved ∿ 2.5 km to the Detector Building. The fixture is used to rotate the coil 90° and install it into the partially assembled iron yoke. The field welds between coils are then made. With the coils in place the nine upper center yoke blocks are installed and bolted to the east uprights. The remaining 18 uprights are erected to form the west wall which is bolted to the rest of the steel. Connection of electrical bus, cooling water hoses and thermal interlock switches completes the installation.

OTHER COMPONENTS

The magnet aperture has inserts containing tapered pole faces, a beam dump and non-ferrous absorbers. The inserts are modularized in length and are removable for servicing. The beam aperture increases from 75 mm horizontal x 305 mm vertical at the entrance to 910 mm horizontal x 1200 mm vertical at the exit.

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